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Assessing Soil Erosion Rates on Manually-Tilled Hillslopes in the Sichuan Hilly Basin Using ^{137}Cs and ^{210}Pb$_{ex}$ Measurements*1

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ABSTRACT

Purple soils are widely distributed in the Sichuan Hilly Basin and are highly susceptible to erosion, especially on the cultivated slopes. Quantitative assessment of the erosion rates is, however, difficult due to small size of the plots of the manually-tilled land, the complex land use, and steep hillslopes. ^{137}Cs and ^{210}Pb$_{ex}$ (excess ^{210}Pb) tracing techniques were used to investigate the spatial pattern of soil erosion rates associated with slope-land under hoe tillage in Neijiang of the Sichuan Hilly Basin. The ^{137}Cs and ^{210}Pb$_{ex}$ inventories at the top of the cultivated slope were extremely low, and the highest inventories were found at the bottom of the cultivated slope. By combining the erosion rates estimates provided by both ^{137}Cs and ^{210}Pb$_{ex}$ measurements, the weighted mean net soil loss from the study slope was estimated to be 3 100 t km^{-2} year^{-1}, which was significantly less than 6 930 t km^{-2} year^{-1} reported for runoff plots on a 10° cultivated slope at the Suining Station of Soil Erosion. The spatial pattern of soil erosion rates on the steep agricultural land showed that hoe tillage played an important role in soil redistribution along the slope. Also, traditional farming practices had a significant role in reducing soil loss, leading to a lower net erosion rate for the field.

Key Words: ^{137}Cs, hoe tillage, ^{210}Pb$_{ex}$, purple soil, soil erosion

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The purple soils (Regosols), developed on Mesozoic Era (Triassic, Jurassic, and Cretaceous) and Tertiary sedimentary rocks are amongst the most fertile soils in southwestern China, especially in the Sichuan Hilly Basin which is one of the most densely populated agricultural regions in China (SRG-IMHE, 1991; Zhang, X. B. *et al.*, 2004; Zhu *et al.*, 2002). However, the purple soils are highly susceptible to erosion and the area represents one of the most severely eroded regions in the Upper Yangtze River Basin. Soil erosion rates were reported to be greater than 5 000 t km^{-2} year^{-1} by the first state soil erosion surveys based on remote sensing undertaken at the end of the 1980s and typically ranged from 3 000 to 5 000 t km^{-2} year^{-1} for the second survey undertaken at the end of the 1990's (Zhang, X. B. *et al.*, 2004). There has been a long history of agriculture in the Sichuan Hilly Basin where manual tillage

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and animal drawn ploughs are predominant due to the small plots and the steep hillslopes. In order to loosen the surface, improve soil physical properties, enhance soil fertility and control weed growth, the farmers till from the bottom of the field, gradually moving up to the top of the slope twice a year (Zhang, J. H. *et al.*, 2004). Many studies have shown that tillage can contribute directly to soil redistribution, but most studies of soil redistribution by tillage have focused on tractor-plough tillage (Mech and Free., 1942; Lindstrom *et al.*, 1992, 2000; Lobb *et al.*, 1995; Revel and Guiresse, 1995; Govers *et al.*, 1994, 1996; Quine *et al.*, 1994; Poesen *et al.*, 1997). Only recently has attention been directed to the understanding of tillage erosion associated with manual tillage and animal-drawn ploughs (Turkelboom *et al.*, 1997; Thapa *et al.*, 1999; Nyssen *et al.*, 2000). Zhang, J. H. *et al.* (2004) assessed tillage translocation and tillage erosion associated with hoeing on steep slopes in the hilly area of Sichuan Basin, using a physical tracer method. Compared to the use of physical tracers, environmental radionuclides offer the potential to quantitatively assess soil redistribution rates at every point on a slope. Thus, radionuclide measurements provide a means of establishing the combined effects of tillage erosion and water erosion on the spatial pattern of soil erosion on cultivated slopes.

As an artificial radionuclide with a half-life of 30.2 years produced by nuclear fission, ^{137}Cs (Energy yield = 0.622 MeV) has been widely used in soil erosion and sedimentation research (Fang *et al.*, 2006; Ritchie and McHenry, 1990; Walling *et al.*, 2003; Zapata, 2002, 2003; Zhang *et al.*, 1998). In contrast, although it has been extensively used for dating sediment cores, the application of ^{210}Pb in soil erosion investigations has received much less attention and requires further investigation and validation. ^{210}Pb (half-life 22.3 year) is a natural product of the ^{238}U decay series that is derived from the decay of gaseous ^{222}Rn (half-life 3.8 d), the daughter of ^{226}Ra (half-life 1 622 year). ^{226}Ra exists naturally in soils and rocks and the ^{210}Pb in soils generated *in situ* by the decay of ^{226}Ra is designated as supported ^{210}Pb. This supported ^{210}Pb will be in equilibrium with the ^{226}Ra. However, upward diffusion of a small portion of the ^{222}Rn produced in the soils and rocks introduces ^{210}Pb into the atmosphere, and its subsequent deposition as fallout provides an input of this radionuclide to surface soils and sediments that will not be in equilibrium with its parent ^{226}Ra. This fallout-derived ^{210}Pb is commonly termed unsupported or excess ^{210}Pb (^{210}Pb$_{ex}$) when incorporated into soils in order to distinguish it from the ^{210}Pb produced *in situ* by the decay of ^{226}Ra (Appleby and Oldfield, 1992). ^{210}Pb$_{ex}$ has been widely used to establish the chronology of lake, estuarine, and marine sediments deposited during the past 100–150 years, but as indicated above, its potential as a tracer for estimating soil erosion rates has received only limited attention. Several researchers have, however, recently attempted to exploit this potential using ^{210}Pb$_{ex}$ both independently and in combination with ^{137}Cs measurements (Walling and He, 1999; Walling *et al.*, 2003; Zhang *et al.*, 2003a). Like ^{137}Cs, ^{210}Pb$_{ex}$ reaching the land surface as fallout from the atmosphere will be rapidly adsorbed by clay minerals and organic matter in the surface soil. Its subsequent redistribution, both within the soil profile and across the land surface, will be controlled by its interaction with tillage and related land use practices, soil erosion, and sediment transport processes. Unlike ^{137}Cs, the ^{210}Pb$_{ex}$ inventory within a stable uneroding soil can be assumed to be in steady state, with fallout inputs balanced by radioactive decay of the existing ^{210}Pb$_{ex}$ inventory. Environmental radionuclides have been widely used in soil erosion and sedimentation investigations and joint use of multi-radionuclides offers considerable potential (Walling and He, 1999; Zhang *et al.*, 2003a).

The objectives of this paper were to evaluate the soil redistribution rates associated with manual tillage on purple soils using ^{137}Cs and ^{210}Pb$_{ex}$ measurements, to study the combined effects of hoe tillage and water erosion on the pattern of soil erosion on cultivated slopes with purple soils, and to further confirm the potential for ^{210}Pb$_{ex}$ measurement to estimate soil redistribution rates.

MATERIALS AND METHODS

The study field

A sloping field on the side of a small hill within the Shangqiao small catchment was selected as the focus of the investigation (29° 35′ N and 105° 03′ E). Shangqiao Gully, the small catchment near the Shangqiao Village, Neijiang, Sichuan Province has a drainage area of 0.29 km^2 and its elevation ranges between 320 and 380 m. The mean annual precipitation for the study area is estimated to be about 1 064 mm, with most precipitation occurring between June and September. The catchment is underlain by horizontally bedded mudstones, siltstones and sandstones of the upper Jurassic Suining and Shaximiao formations. The soils in the study area, derived from purple mudstone and sandstone, are generally shallow and are classified as Regosols in FAO soil classification.

The study field, located on the lower side of a cultivated slope, has a length of 64 m and three slope inflections along its length at 5, 15 and 31 m. It consists of four subfields: the first subfield has a length of 5 m and a gradient of 5°, the second subfield has a length of 10 m and a gradient of 21°, the third subfield had a length of 16 m and a gradient of 12°, and the fourth subfield has a length of 33 m and a gradient of 8° (Fig. 1). The three inflection points are located near sites 1, 3 and 5, respectively.

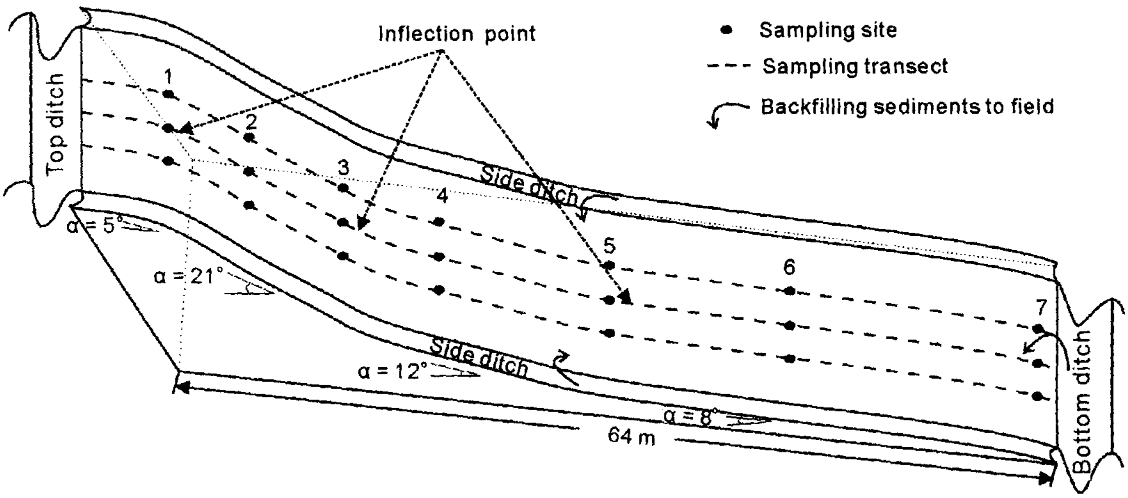


Fig. 1 The study field where the sediments deposited in the contour ditches and side ditches would be backfilled to the field by farmers during the following year.

There has been a long history of agriculture and both animal-drawn and manual tillage such as hoeing in the study area, which is characterized by short slope lengths and narrow slope widths. Farmers traditionally till from the bottom of the field and gradually moving to the top of the slope. As tillage occurs, the tilled soil is always moved downslope. This is quite different from the tillage operations associated with tractor-ploughs in mechanized agriculture, where the soil is tilled in opposing directions on successive occasions (Zhang, J. H. *et al.*, 2004). In addition, most sloping fields in the Sichuan Hilly Basin are managed using traditional erosion control practices, involving contour ditches, and the sediments deposited in these contour ditches and side ditches are returned to the field each year.

To document the key features of the spatial pattern of post-fallout redistribution of ^{137}Cs and $^{210}Pb_{ex}$ within the study field, a total of 21 sectioned soil cores were collected along three parallel downslope transects, spaced 1 m apart in May 2004. To establish the local ^{137}Cs and $^{210}Pb_{ex}$ reference inventories, one sectioned core was collected from an undisturbed area near the Masson pine (*Pinus massoniana* Lamb.) forest of Changba Hill, Guobei Town, Neijiang City, and six bulk soil cores were collected from grassland and flat cultivated land at this location.

Methods

The sectioned cores collected from the cultivated sloping field were obtained using an 8 cm diameter corer. The core tube was propelled into the ground manually and the resulting soil cores were sectioned into three depth increments of 20–25 cm. The sectioned cores collected from the reference site were collected using an 8 cm diameter corer. The tube was propelled into the ground manually and the resulting soil cores were sectioned into 8 sections at 3 or 5 cm increments. Bulk cores were collected using an 8 cm diameter corer. The core tube was again propelled into the ground manually, but the soil cores were not sectioned. Processing of the soil cores was undertaken in the laboratories of the Chengdu Institute of Mountain Hazards and Environment, Chinese Academy of Sciences. All samples were air-dried, ground and weighed, prior to analysis. $^{210}Pb_{ex}$ and ^{137}Cs activities were measured by gamma spectrometry in the Sediment Research Laboratory of the Department of Geography at the University of Exeter, UK. The individual samples, which each had a mass of about 200 g, were transferred into airtight plastic pots and sealed for a period of $\geq$ 20 days prior to assay, in order to achieve equilibrium between ^{226}Ra and its daughter ^{222}Rn. Measurements of $^{210}Pb_{ex}$ and ^{137}Cs activity in the soil samples were undertaken simultaneously using a high resolution, low background, low energy, hyper-pure n-type germanium coaxial γ-ray detector (Ortec LOAX HPGe). The samples were counted for $\geq$ 50 000 s, providing a precision of approximately $\pm$5% at the 95% level of confidence for the measurements. The ^{137}Cs concentrations were measured at 662 keV. The total ^{210}Pb activity of the samples was measured at 46.5 keV and the ^{226}Ra concentration was assayed at 351.9 keV, by measuring ^{214}Pb, a short-lived daughter of ^{226}Ra. The unsupported ^{210}Pb ($^{210}Pb_{ex}$) concentration of a sample was calculated by subtracting the ^{226}Ra-supported ^{210}Pb concentration from the total ^{210}Pb concentration.

RESULTS AND DISCUSSION

Local ^{137}Cs and $^{210}Pb_{ex}$ reference inventories

The ^{137}Cs and $^{210}Pb_{ex}$ inventories documented for the sectioned soil core collected from the undisturbed grassland were 2 243.9 $\pm$ 99.7 Bq m^{-2} and 19 214.3 $\pm$ 960.6 Bq m^{-2}, respectively. In the grassland and the flat cultivated land near the Masson pine forest of Changba Hill, Guobei Town, Neijiang city, the ^{137}Cs inventories range between 1 776.3 $\pm$ 115.8 Bq m^{-2} and 2 294.2 $\pm$ 164.5 Bq m^{-2}, and the $^{210}Pb_{ex}$ inventories range between 17 082.3 $\pm$ 904.5 Bq m^{-2} and 22 014.1 $\pm$ 1 156.6 Bq m^{-2}. These values are very similar to the value for the sectioned core collected from the undisturbed grassland near the Masson pine forest of Changba Hill. The mean ^{137}Cs and $^{210}Pb_{ex}$ inventories for the 7 soil cores (*i.e.*, 1 sectioned and 6 bulk cores), providing values of 2 065.6 Bq m^{-2} and 18 902.2 Bq m^{-2} for ^{137}Cs and $^{210}Pb_{ex}$, respectively, have been used as the reference inventories of ^{137}Cs and $^{210}Pb_{ex}$.

At other locations in the Sichuan Hilly Basin, a ^{137}Cs reference inventory reported values of 2 600 Bq m^{-2} for a site at Yanting measured in 1991 (Qi *et al.*, 2006), 2 035.8 Bq m^{-2} for a site at Nanchong measured in 1997 (Zhang *et al.*, 2003b), 2 300 Bq m^{-2} for a site at Jinfeng measured in 1992 (Li *et al.*, 1995), 2 163 Bq m^{-2} for a site at Changshou measured in 1994 (Li *et al.*, 1995), 1 924.6 Bq m^{-2} for a site at Kaixian measured in 2000 (Qi *et al.*, 2006), and 1 820.4 Bq m^{-2} for a site at Jianyang measured in 2002 (Zhang *et al.*, 2006). Corrected for decay to 2004, these values are 1 929.02, 1 733.70, 1 746.04, 1 719.58, 1 638.39 and 1 738.31 Bq m^{-2}, respectively (Fig. 2 and Table I). All these values are close to the value obtained for the study area (*i.e.*, 2 065.60 Bq m^{-2}). Walling and He proposed a method for estimating bomb-derived ^{137}Cs reference inventories for areas where suitable reference sites are difficult to identify (Zapata, 2002). Taking into account the dominant factors influencing the deposition of ^{137}Cs from the atmosphere such as precipitation, longitude and latitude, the model developed by Sarmiento and Gwinn (1986) for describing the relationship between ^{90}Sr deposition and precipitation was used in conjunction with existing global-scale information on the distribution of bomb-derived ^{137}Cs inventories and the global pattern of precipitation to obtain estimates of bomb-derived ^{137}Cs inventories for a study area (Zapata, 2002). For the local study field, the measured reference inventory and model-estimated reference inventory are 2 065.60 and 840.63 Bq m^{-2}, respectively. Most of the model-estimated inventories for the Sichuan Hilly Basin are closely comparable with the measured reference inventories, except in the case of Changshou (29° 01′ N and 106° 64′ E) and Neijiang (29° 35′ N and 105° 03′ E). The Sichuan Hilly Basin is surrounded by mountains and is well known for its cloudy and wet weather.

The lower reference inventories estimated for Changshou (29° 01′ N and 106° 64′ E) and Neijiang (29° 35′ N and 105° 03′ E) using the model proposed by Walling and He maybe result from the subdivision of the prediction model at 30° N. The reference inventories for other locations at latitude higher than 30° and between 30° N and 32° N are close to the measured values. The measured reference inventory for Neijiang is similar to those values for the other six locations, despite the fact that the value estimated using the model is much less than those at the other sites.

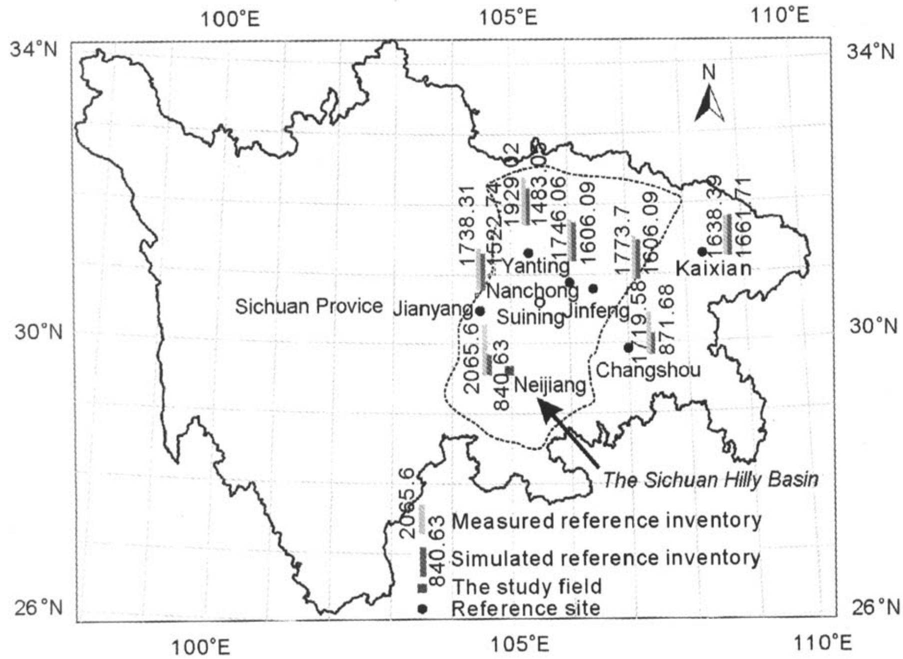


Fig. 2 The location of the study area and the measured ^{137}Cs reference inventories (Bq m^{-2}) reported for nearby regions: Yanting (Qi *et al.*, 2006), Nanchong (Zhang *et al.*, 2003b), Changshou (Lu and Higgitt, 2000), Jinfeng (Li *et al.*, 1995), Kaixian (Qi *et al.*, 2006), and Jianyang (Zhang *et al.*, 2006) and the reference inventories (Bq m^{-2}) simulated using the Cs-137 erosion calibration model (Zapata, 2002).

TABLE I

Comparison between model-estimated reference inventories (Ae) and measured reference inventories (Am) for ^{137}Cs

Site	Longitude	Latitude	Rainfall	Am[a]	Ae
	°		mm	Bq m^{-2}	
Nanchong	106.07	30.80	1 010.00	1 733.70	1 606.09
Jinfeng	106.07	30.80	1 010.00	1 746.04	1 606.09
Yanting	105.50	31.25	825.80	1 929.02	1 483.05
Changshou	106.64	29.01	1 165.00	1 719.58	871.68
Kaixian	108.39	31.23	1 100.00	1 638.39	1 661.71
Neijiang	105.05	29.58	1 064.00	2 065.60	840.63
Jianyang	104.53	30.38	883.00	1 738.31	1 522.74

[a] All measured reference inventories are corrected for decay to 2004.

Unlike ^{137}Cs, little information about ^{210}Pb$_{ex}$ reference inventories has been reported for the Sichuan Hilly Basin and the availability of any such information is very limited for both China and the world. However, a value of 12 859.9 Bq m^{-2} has been documented for Jianyang in the Sichuan Hill Basin of China (Zhang *et al.*, 2006), a ^{210}Pb$_{ex}$ reference inventory of 5 730 Bq m^{-2} has been reported for a site in the Loess Plateau (Zhang, *et al.*, 2003a) and a value of 34 000 Bq m^{-2} has been documented for Taiwan Province in China (Huh and Su, 2004). Appleby and Oldfield (1992) indicated that annual ^{210}Pb$_{ex}$ deposition fluxes are significantly reduced over the oceans, due to the lack of a terrestrial source of ^{210}Pb, and generally increase from the west to east over the continents, due to the predominant west-east air mass trajectory. The reference inventory of 18 902.2 Bq m^{-2} documented for the study site is therefore amongst the highest reported and is similar to the value of 12 859.9 Bq m^{-2} reported for Jiajia Village in Jianyang (Zhang *et al.*, 2006), although it is much less than the value of 34 000 Bq m^{-2} reported for Yanminshan in Taiwan Province where the annual precipitation is 4 500 mm (Huh and Su, 2004).

The depth distribution of ^{137}Cs and $^{210}Pb_{ex}$ concentrations in soil cores

Depth distributions of ^{137}Cs and $^{210}Pb_{ex}$ were very similar in both uncultivated and cultivated soils (Fig. 3). The profile for the uncultivated soil of the grassland showed that the maximum concentrations of the two radionuclides occurred in the surface horizon and decreased exponentially with depth. ^{137}Cs and $^{210}Pb_{ex}$ concentrations in the surface horizon were 24.90 ± 0.91 Bq kg^{-1} and 291.02 ± 12.69 Bq kg^{-1}, respectively.

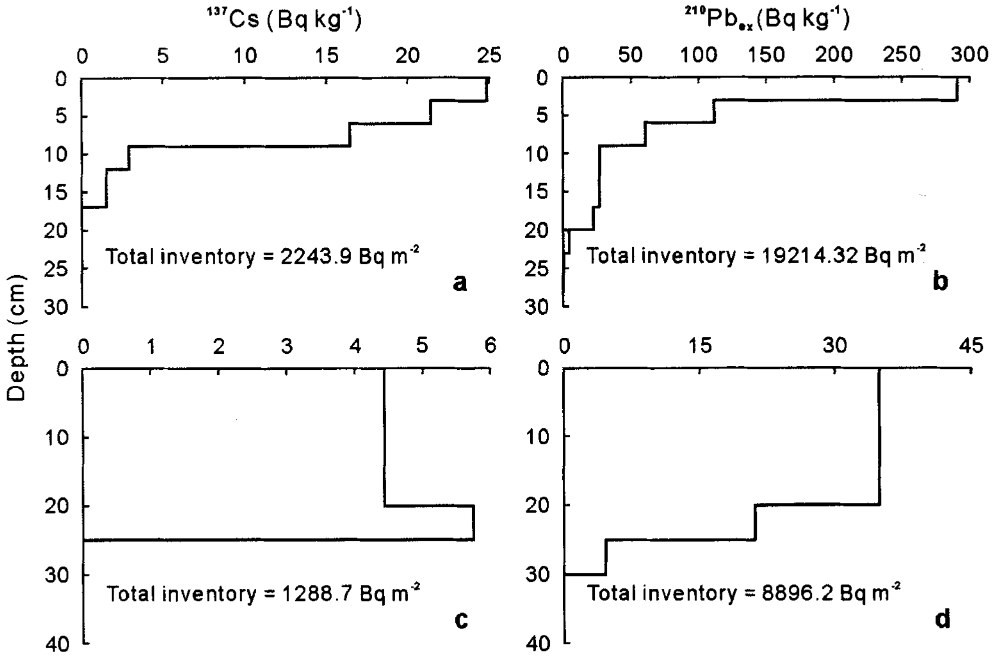


Fig. 3 The depth distribution of ^{137}Cs and $^{210}Pb_{ex}$ concentrations for the reference sites (a, b) and those for the middle site (site 4) on the cultivated slope (c, d).

At the eroding middle site (site 4), the two radionuclides were evenly distributed within the 20-cm deep plough layer (Fig. 3). Here, the maximum ^{137}Cs concentration was found in the 20–25 cm deep layer, while the maximum $^{210}Pb_{ex}$ concentration was found in the 0–20 cm layer and there were relatively small quantities of $^{210}Pb_{ex}$ below the 20 cm layer. During the Chinese "Great Leap Forward" from 1958 to 1960, a deep ploughing campaign was widely applied in the local area. During this time the plough depth on the cultivated slopes exceeded 20 cm and sometimes even reached 30 cm. This may explain the higher ^{137}Cs concentration found in the 20–25 cm deep layer and reported here. The small quantity of $^{210}Pb_{ex}$ in the 25–30 cm layer possibly results from the downward diffusion of $^{210}Pb_{ex}$ from the plough layer. At the beginning of cultivation, $^{210}Pb_{ex}$ was mixed uniformed in the plough layer and there was no $^{210}Pb_{ex}$ beneath the plough layer. Following cultivation, $^{210}Pb_{ex}$ gradually diffused below the plough layer and the concentration there gradually increased. For the depth profile from the accumulated toe site (site 7), the ^{137}Cs concentration in the top 20 cm layer was close to those observed at the middle site of the sloping field, and the maximum concentration of 7.13 ± 0.29 Bq kg^{-1} was found at the 20–30 cm depth. Concentrations significantly declined below that depth. The greater ^{137}Cs concentration in the 20–30 cm deep layer indicates that the ^{137}Cs concentration in the ploughed soil has decreased since the middle of 1960s. Like ^{137}Cs, $^{210}Pb_{ex}$ at site 7 was evenly distributed in the top 20 cm layer. Its concentration was close to those found at the middle site and the maximum concentration of 48.48 ± 1.85 Bq kg^{-1} occurred in the 25–30 cm deep layer.

Downslope variations of ^{137}Cs and $^{210}Pb_{ex}$ inventories

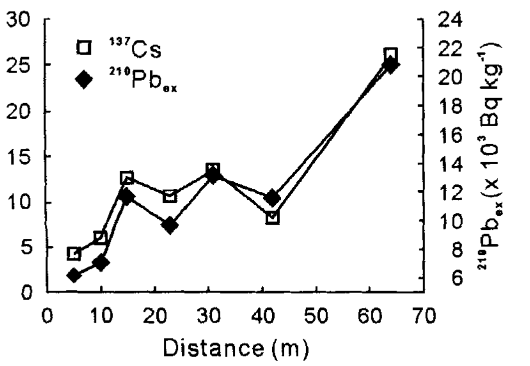
The ^{137}Cs and $^{210}Pb_{ex}$ inventories measured in the study field and their downslope variations are shown in Table II and Fig. 4. These suggest that the ^{137}Cs and $^{210}Pb_{ex}$ inventories have a similar tendency to increase downslope, providing two peak values in front of the two inflection points that are located at 15 and 31 m from the top of the slope. At site 1, the mean ^{137}Cs and $^{210}Pb_{ex}$ inventories were 407.9 and 6 184.7 Bq m^{-2}, respectively, and they accounted for 18.1% and 32.1% of the reference inventories. At site 3, the mean ^{137}Cs and $^{210}Pb_{ex}$ inventories were 1 223.5 and 11 685.69 Bq m^{-2}, accounting for 54.5% and 60.8% of the reference values. At site 5, the mean ^{137}Cs and $^{210}Pb_{ex}$ inventories were 1 301.6 and 13 191.1 Bq m^{-2}, accounting for 58% and 68.6% of the reference inventories. The degree of depletion of the ^{137}Cs and $^{210}Pb_{ex}$ inventories relative to the reference inventories reflects the magnitude of the net soil losses associated with both water and tillage erosion (Quine *et al.*, 1994; Zhang, J. H. *et al.*, 2004). Hoeing, the predominant tillage practice in the local area, exerts an important influence on the spatial distribution of soil erosion down the rolling slope. Tilled soils are always moved downslope because farmers are in the habit of tilling from the bottom of the field and gradually moving up the slope (Zhang, J. H. *et al.*, 2004). The lowest ^{137}Cs and $^{210}Pb_{ex}$ inventories reported for site 1 and the lower ^{137}Cs and $^{210}Pb_{ex}$ inventories reported for site 4 indicate that the soils on the ridge top have

TABLE II

Comparison of the measured ^{137}Cs and $^{210}Pb_{ex}$ inventories and the estimated annual soil erosion rates using these values

Sampling site	Distance	Inventory		Annual soil losses	
		^{137}Cs	$^{210}Pb_{ex}$	by ^{137}Cs	by $^{210}Pb_{ex}$
	m	Bq m^{-2}		cm year^{-1}	
1	5	407.90	6 184.87	0.68	0.78
2	10	582.11	7 063.63	0.52	0.65
3	15	1 223.46	11 685.69	0.22	0.27
4	23	1 027.86	9 692.95	0.30	0.40
5	31	1 301.63	13 191.04	0.20	0.19
6	42	799.84	11 606.02	0.39	0.30
7	64	2 526.70	20 836.88	+[a]	+

[a] + indicates deposition at a site.



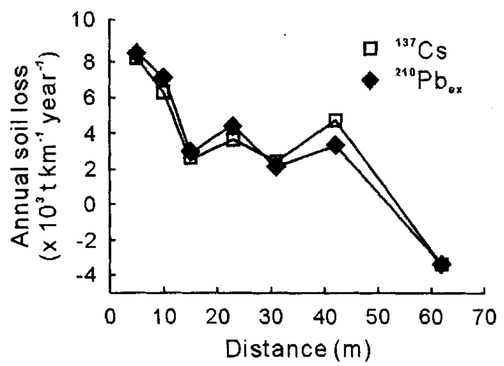


Fig. 4 Downslope change of ^{137}Cs and $^{210}Pb_{ex}$ inventories.

Fig. 5 Downslope change of soil erosion rates derived from ^{137}Cs and $^{210}Pb_{ex}$.

gradually been removed by hoeing and that soils depths on the convexities have declined. Conversely, the highest ^{137}Cs and $^{210}Pb_{ex}$ inventories found at site 7 show that the greatest soil accumulation occurred at the bottom of the hillslope.

Soil erosion rates

The accuracy of erosion rate estimates derived using environmental radionuclides depends primarily upon the reliability of the calibration relationship employed, but it will also reflect the spatial variability of ^{137}Cs fallout, the degree of selective mobilization and transport of the fine material, and the precision and detection limits of gamma counting (Zhang *et al.*, 1990; Yang *et al.*, 2004; Zhang, X. B. *et al.*, 2004, Fang *et al.*, 2006). At an eroding site in the study field, the ^{137}Cs inventories found in the plough layer will reflect the loss of soil containing radiocaesium from the soil profile by water erosion and/or soil redistribution by tillage. In this study, a mass balance approach was used to estimate soil erosion rates within the study field from the measurements of the ^{137}Cs inventory, and the average depth of annual soil loss at the sampling points were estimated using the simplified mass balance model proposed by Zhang *et al.* (1990):

$$A = A_{\text{ref}}(1 - h/H)^{y-1963} \tag{1}$$

where A is the ^{137}Cs inventory (Bq m^{-2}), A_{ref} is the local ^{137}Cs reference inventory (Bq m^{-2}), h is the annual soil loss depth (cm), H is the plough depth (18 cm), and y is the sampling year. In this simplified model, it is assumed that the entire fallout input of ^{137}Cs occurred in 1963 because a major proportion of bomb-derived ^{137}Cs was deposited in a short period extending only a few years on either side of 1963 (Zhang *et al.*, 1990).

The estimates of mean annual soil loss at the sampling points in the study field where the measured inventories are less than the reference inventory indicate that most of the site has experienced net soil loss. These soil loss estimates range between 0.20 and 0.68 cm year^{-1} in the study field (Table II).

In contrast to the behavior of ^{137}Cs, the $^{210}Pb_{ex}$ inventories at the eroding sites within the study field can be expected to have been in a near steady state over a period of more than 100 years, with the annual $^{210}Pb_{ex}$ loss due to soil loss and radioactive decay being balanced by the annual $^{210}Pb_{ex}$ deposition flux. For cultivated land, the $^{210}Pb_{ex}$ content is almost uniform throughout the plough layer as a result of mixing associated with the plough. The mean annual depth of soil loss at an eroding site can therefore be estimated using the following model (Walling and He, 1999; Zapata, 2002; Zhang *et al.*, 2003a):

$$h = \lambda H_0(A_{\text{ref}} - A)/(A + H_0 2\lambda C\gamma) \tag{2}$$

where h is the annual soil loss depth (cm); A is the $^{210}Pb_{ex}$ inventory (Bq m^{-2}) at the sampling site; A_{ref} is the local $^{210}Pb_{ex}$ reference inventory (Bq m^{-2}); λ is the radioactivity decay coefficient (0.0307); H_0 is the plough depth (18 cm); C is the $^{210}Pb_{ex}$ concentration of surface soil (mBq g^{-1}); and γ is the bulk density of soil (1.15 g cm^{-3}).

The possibility that a proportion of the freshly deposited ^{137}Cs and $^{210}Pb_{ex}$ fallout is removed by erosion prior to incorporation in the plough layer by the annual ploughing has been ignored in Eqs. 1 and 2. However, since a significant proportion of the accumulated sediments in the bottom trench are returned to the field each year, any associated overestimation of erosion rates is thought to be minimal. Based on Eq. 2, the estimates of average annual soil losses provided by the $^{210}Pb_{ex}$ measurements for the coring sites in the field, where the measured inventories were less than the reference inventory, ranged between 0.19 and 0.78 cm year^{-1} in the field (Table II).

The ^{137}Cs and $^{210}Pb_{ex}$ measurements undertaken on the cores indicate a greater soil depth at the bottom of the slope (site 7) due to the accumulation of sediment. By comparing the ^{137}Cs depth distribution at site 7 with that at the reference site, we estimate that about 12 cm of sediment has accumulated there since 1963. Thus, an average deposition rate of 0.29 cm $year^{-1}$ has been estimated for the average deposition rate of this cultivated slope over the past 41 years.

Figs. 4 and 5 show that the $^{210}Pb_{ex}$ inventories and the estimates of annual rates of soil loss provided by the $^{210}Pb_{ex}$ measurements are closely comparable to those derived from the ^{137}Cs measurements and are consistent with existing knowledge of the study area. The results obtained from this study further confirm the potential for using $^{210}Pb_{ex}$ measurements to estimate soil erosion rates over the medium-term timescale of 50–100 years. The mean annual rates of net soil loss estimated from the ^{137}Cs and $^{210}Pb_{ex}$ measurements are 3 190 and 3 012 t km^{-2} $year^{-1}$, respectively. By averaging the soil erosion rate estimated from the ^{137}Cs and $^{210}Pb_{ex}$ measurements for the individual coring sites, the weighted mean rate of net soil loss for the sloping field is 3 101 t km^{-2} $year^{-1}$. According to the erosion plot measurements undertaken at the Suining Soil and Water Conservation station, the long-term average soil loss form 10° cultivated slopes with purple soils was 6 930 t km^{-2} $year^{-1}$ (SSWCC, 1991). The net soil erosion rate of 3 101 t km^{-2} $year^{-1}$ for the study field, with its average gradient of 10.5°, estimated using the radionuclide measurements was 55% less than the rate of soil loss provided by the Suining long-term monitoring data. Most of the sloping fields in the Sichuan Hilly Basin are managed using traditional erosion control measures, involving contour ditches, side ditches and the practice of "backfilling sediment to field" (Tiaoshamiantu), by which the sediment deposited in the contour ditches and side ditches is returned to the field each year (Zhang *et al.*, 2006). The lower soil erosion rates estimated using both radionuclides indicate that these traditional erosion control measures may have a considerable effect in reducing net soil lost from a field in the purple soil hilly region.

Water erosion versus tillage erosion

Intensive non-mechanized cultivation depends upon the available labour, but it has been widely used in the Sichuan Hilly Basin due to the lack of resources and the small size of the fields. Animal-drawn ploughs and manual tillage, particularly hoeing, are the predominant tillage methods in the local area. Deep ploughing campaign, which occurred during the period of "the Great Leap Forward" is likely to have resulted in the deeper distribution of ^{137}Cs in the middle of the cultivated slope. Tillage increases the surface depression storage as well as the infiltration capacity of the soil surface roughness (Turkelboom *et al.*, 1997). At the same time, tillage also decreases the soil's resistance to detachment by raindrop impact or flowing water (Govers *et al.*, 1994). Runoff water is able to transport eroded soil over longer distances, and eroded sediment is more likely to reach a stream (Turkelboom *et al.*, 1997). Unlike water erosion, where soil erosion rates typically increase with slope length, tillage erosion due to hoeing translocates a thin surface layer of soil of fairly uniform thickness, from the top to the bottom of the field.

The study field is a compound assemblage of concavities and convexities. The upper part of it is a convex slope and the middle and lower parts are concave slopes. At site 1, which is near the inflection point of the upper convex slope, redistribution of soil by hoeing is the primary cause of the lowest ^{137}Cs and $^{210}Pb_{ex}$ inventories and the highest soil erosion rates. This is because soils have been gradually removed by hoeing from the ridge top and the soils on the convexities have been reduced to a thin layer. At the second (site 3) and third (site 5) inflection points, the soil erosion rates are lower than those at site 4 and site 6, due to the net effects of both tillage translocation and water erosion. At the base of the convexity (site 3) and the middle of the concavity (site 5), some of the sediments mobilized by hoe tillage and water erosion are deposited, counteracting some of the soils lost by tillage and water erosion, thus resulting in lower rates of soil loss than those reported for sites 4 and 6. At the bottom of the cultivated slope, the ^{137}Cs and $^{210}Pb_{ex}$ inventories were greater than the reference inventories, suggesting that deposition was occurring here. The higher values for site 7 reflect the gradual accumulation of soil redistribution by hoe tillage and water erosion at the bottom of the slope and the return of some sediment trapped in the bottom ditch that has been returned to the field by the farmers.

CONCLUSIONS

Soil redistribution rates were estimated using ^{137}Cs and $^{210}Pb_{ex}$ measurements on a cultivated slope located near Shangqiao Village, Neijiang City, Sichuan Province. The lowest ^{137}Cs and $^{210}Pb_{ex}$ inventories were observed at the top of the slope and the highest ^{137}Cs and $^{210}Pb_{ex}$ inventories were seen at the bottom of the slope, indicating that the hoeing tillage exerted a significant influence on the pattern of soil redistribution along this cultivated slope on purple soils. By combining the estimates of soil erosion rates provided by the ^{137}Cs and $^{210}Pb_{ex}$ measurements, the weighted mean net soil loss for this hillslope was estimated to be 3 101 t km^{-2} year^{-1}, which is considerably less than the erosion rates estimated from runoff plot measurements elsewhere in the Sichuan Hilly Basin. The lower soil erosion rate for the cultivated purple soil slope showed that some farming practices, especially "backfilling sediment to field", could have an important role in reducing soil loss and conserving valuable cultivated soil on sloping fields in the Sichuan Hilly Basin. The inventories of $^{210}Pb_{ex}$ and the soil erosion rates estimated using the $^{210}Pb_{ex}$ measurements were closely comparable to those derived from ^{137}Cs, and this finding further confirmed the potential of using $^{210}Pb_{ex}$ measurements to estimate soil redistribution rates over a medium-term timescale of 50–100 years.

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REFERENCES

Appleby, P. G. and Oldfield, F. 1992. Application of Lead-210 to sedimentation studies. *In* Ivanovich, M. and Harman, R. S. (eds.) Uranium-series Disequilibrium: Application to Earth, Marine and Environmental Sciences. Clarendon Press, Oxford, UK. pp. 731–738.

Fang, H. J., Yang, X. M., Zhang, X. P. and Liang, A. Z. 2006. Using ^{137}Cs tracer technique to evaluate erosion and deposition of black soil in Northeast China. *Pedosphere*. **16**: 201–209.

Govers, G., Vandaele, K., Desmet, P. J. J., Poesen, J. and Bunte, K. 1994. The role of tillage in soil redisbution on hillslopes. *Soil Science*. **45**: 469–478.

Govers, G., Quine, T. A., Desmet, P. J. J. and Walling, D. E. 1996. The relative contribution of soil tillage and overland flow erosion to soil redistribution on agricultural land. *Earth Surf. Pro. Landforms*. **21**: 929–946.

Huh, C. A. and Su, C. C. 2004. Distribution of fallout radionuclides (^{7}Be, ^{137}Cs, ^{210}Pb, $^{239,240}Pu$) in soils of Taiwan. *Journal of Environmental Radioactivity*. **77**: 87–100.

Li, Q. Y., Jiang, S. Q. and Sun, H. C. 1995. Determination of surface erosion of the small watersheds in the hilly area of purple soils in the upper reaches of the Yangtze River. *Journal of Yangtze River Scientific Research Institute* (in Chinese). **12**(11): 51–56.

Lindstrom, M. J., Nelson, W. W. and Schumacher, T. E. 1992. Quantifying tillage erosion rates due to moldboard plowing. *Soil & Tillage Research*. **24**: 243–255.

Lindstrom, M. J., Schumacher, J. A. and Schumacher, T. E. 2000. TEP: A tillage erosion prediction model to calculate soil translocation rates from tillage. *Journal of Soil and Water Conservation*. **55**: 105–108.

Lobb, D. A., Kachanoski, R. G. and Miller, M. H. 1995. Tillage translocation and tillage erosion on shoulder slope landscape positions measured using ^{137}Cs as a tracer. *Canadian Journal of Soil Science*. **75**: 211–218.

Lu, X. and Higgitt, D. 2000. Estimating erosion rates on sloping agricultural land in the Yangtze Three Georges, China, from caesium-137 measurement. *Catena*. **39**: 33–51.

Mech, S. J. and Free, G. R. 1942. Movement of soil during tillage operations. *Agricultural Engineering*. **23**: 379–382.

Nyssen, J., Poesen, J., Haile, M., Moeyersons, J. and Deckers, J. 2000. Tillage erosion on slopes with soil conservation structures in the Ethiopian highlands. *Soil & Tillage Research*. **57**: 115–127.

Poesen, J., Van Wesemael, B., Govers, G., Martinez-Fernandez, J., Desmet, P. J. J., Vandaele, K., Quine, T. A. and Degraer, G., 1997. Patterns of rock fragment cover generated by tillage erosion. *Geomorphology*. **18**: 183–197.

Qi, Y. Q., Zhang, X. B., He, X. B., Wen, A. B. and Fu, J. X. 2006. ^{137}Cs reference inventories distribution pattern in China. *Nuclear Techniques* (in Chinese). **29**(1): 42–50.

Quine, T. A., Desmet, P. J. J., Govers, G., Vandaele, K. and Walling, D. E. 1994. A comparison of the roles of tillage and water erosion in landform development and sediment export on agricultural land near Leuven, Belgium. *In* Olive, L. J., Loughran, R. J. and Kesby, J. A. (eds.) Variability in Stream Erosion and Sediment Transport, Proceedings of the Canberra Symposium. No. 224. IAHS Publication, pp.77–86.

Revel, J. C. and Guiresse, M. 1995. Erosion due to cultivation of calcarcous clay soils on the hillsides of south west France. I. Effect of former farming practices. *Soil & Tillage Research.* **35**: 147–155.

Ritchie, J. C. and McHenry, J. R. 1990. Application of radioactive fallout caesium-137 for measuring soil erosion and sediment accumulation rates and patterns: A Review. *Journal of Environmental Quality.* **19**: 215–233.

Sarmiento, J. L. and Gwinn, E. 1986. Strontium 90 fallout prediction. *Journal of Geophysical Research.* **91**: 7 631–7 646.

Sichuan Soil and Water Conservation Committee (SSWCC). 1991. Monitoring Report of Soil and Water Conservation in Sichuan Province(in Chinese). Sichuan Publishing House of Science & Technology Chengdu. 773pp.

Soil Research Group of Institute of Mountain Hazards and Environment, CAS (SRG-IMHE). 1991. Purple Soils in China (in Chinese). Vol. 1. Science Press, Beijing. 349pp.

Thapa, B. B., Cassel, D. K. and Garrity, D. P., 1999. Ridge tillage and contour natural grass barrier strips reduce tillage erosion. *Soil & Tillage Research.* **51**: 341–356.

Turkelboom, F., Poesen, J., Ohler, I., Van Keer, K., Ongprasert, S. and Vlassak, K. 1997. Assessment of tillage erosion rates on steep slopes in northern Thailand. *Catena.* **29**: 29–44.

Walling, D. E. and He, Q. 1999. Using fallout lead-210 measurements to estimate soil erosion on cultivated land. *Soil Sci. Soc. Am. J.* **63**: 1 404–1 412.

Walling, D. E., Collins, A. L. and Sichingabula, H. M. 2003. Using unsupported lead-210 measurements to investigate soil erosion and sediment delivery in a small Zambian catchment. *Geomorphology.* **52**: 193–213.

Yang, H., Du, M. Y., Chang, Q., Minami, K. and Hatta, T. 2004. Quantitative model for estimating soil erosion rates using ^{137}Cs. *Pedosphere.* **8**(3): 211–220.

Zapata, F. 2002. Handbook for the Assessment of Soil Erosion and Sedimentation Using Environmental Radionuclides. Kluwer Academic Publishers. Dordrecht. 219pp.

Zapata, F. 2003. The use of environmental radionuclides as tracers in soil erosion and sedimentation investigation: recent advances and future developments. *Soil & Tillage Research.* **69**: 3–13.

Zhang, J. H., Lobb, D. A., Li, Y. and Liu, G. C. 2004. Assessment of tillage translocation and tillage erosion by hoeing on the steep land in hilly areas of Sichuan, China. *Soil & Tillage Research.* **75**(2): 99–107.

Zhang, X. B., Higgitt, D. L. and Walling, D. E. 1990. A preliminary assessment of potential for using Caesium-137 to estimate rates of soil erosion in the Loess Plateau of China. *Hydrological Sciences.* **35**(3): 243–252.

Zhang, X. B., Quine, T. A. and Walling, D. E. 1998. Soil erosion rates on sloping cultivated land on the Loess Plateau near Ansai, Shaanxi Province, China: An investigation using ^{137}Cs and rill measurements. *Hydrology Proceedings.* **12**(1): 171–189.

Zhang, X. B., Walling, D. E., Feng, M. Y. and Wen, A. B. 2003a. $^{210}Pb_{ex}$ depth distribution in soil and calibration models for assessment of soil erosion rates from $^{210}Pb_{ex}$ measurements. *Chinese Science Bulletin.* **48**(8): 813–818.

Zhang, X. B., Zhang, Y. Y., Wen, A. B. and Feng, M. Y. 2003b. Assessment of soil losses on cultivated land by using the ^{137}Cs technique in the Upper Yangtze River Basin of China. *Soil & Tillage Research.* **69**: 99–106.

Zhang, X. B., He, X. B., Wen, A. B., Walling, D. E., Feng, M. Y. and Zou, X. 2004. Sediment source identification by using ^{137}Cs and ^{210}Pb radionuclides in a small catchment of the Hilly Sichuan Basin, China. *Chinese Science Bulletin.* **49**(18): 1 953–1 957.

Zhang, X. B., Qi, Y. Q., Walling, D. E., He, X. B., Wen, A. B. and Fu, J. X. 2006. A preliminary assessment of the potential for using $^{210}Pb_{ex}$ measurement to estimate soil redistribution rates on cultivated slopes in the Sichuan Hilly Basin of China. *Catena.* **68**: 1–9.

Zhu, B., Chen, S., You, X., Peng, G. and Zhang, X. W. 2002. Soil fertility restoration on degraded upland of purple soil. *Acta Pedologica Sinica* (in Chinese). **39**(5): 743–749.